The Design and Application of a New Vertical-axis Ship Propeller

Shuyu Liu
Ocean College, Zhejiang University
Hangzhou, China
Email: 21334054@zju.edu.cn

Jianxing Leng
Ocean College, Zhejiang University
Hangzhou, China
Email: jxleng@zju.edu.cn

Jialin Huang
Hangzhou Modern Ship Design and Research Company
Hangzhou, China
Email: hzflg2013@126.com

Haocai Huang(Corresponding author)
Ocean College, Zhejiang University
Hangzhou, China
Email: hchuang@zju.edu.cn

Lixin Chen
Hangzhou Modern Ship Design and Research Company
Hangzhou, China
Email: zjhzclx@126.com

Abstract— **The new vertical-axis propeller is a kind of propulsion device, which can adjust revolving speed continuously to adapt to changeable working conditions under the constant velocity of diesel engine. What's more, its own auxiliary transmission mechanism can realize some extra functions, such as clutch and hybrid power. Based on the propeller's special steering principle and structure, this paper introduces the design of the propeller and its good application in hybrid power system**

Keywords—vertical-axis Propeller; auxiliary transmission mechanism; hybrid power system

I. INTRODUCTION

The Vertical-axis Propeller so called cycloidal propeller is a kind of novel device applied to marine propulsion. Its phase angle can range from 0° to 360°, of which the thrust can be generated in any direction, making the Vertical-axis Propeller combine the function of propulsion and steering at run time. The first patent about vertical-axis propeller was applied by Frederick Kirsten in 1921 [1]. In 1969, Ficken and Dickerson published a paper and indicated that two kinds of Vertical-axis Propeller (VSP) could be used in real ship at that time, one of which is Kirsten-Boeing Propeller and another is Voith-Schneider Propeller[2]. After that VSP got a better development because of the adjustable pitch. In theoretical research, Just gave a calculation by using the wing element theory, and the result was consistent with the experimental results of the Voith Company. In 1971, Mendenhall and Spangler published an unsteady model adopted Dual Circulation Theory to calculate the propeller [3]. In actual application, the VSP was invented based on Kirsten cycloidal propeller by an Austrian engineer called Ernst Leo Schneider in 1927 and then its control performance and manufacturing process has been further improved. Additionally, in the present production of VSP, the Voith Company played a role of monopoly [4-6]. The Voith has produced a six-blade VSP recently with Crank-connecting Rod and developed a Voith Cycloidal Rudder (VCR). The VCR has the same principle with VSP except that the VCR has only two blades to transform between active and passive situation. When it is in active aituation, the VCR will work as a VSP[7].

The Vertical-axis Propeller mentioned in this paper consists of four vertical blades, of which the rotating axis is perpendicular to the ship hull as the same with VSP. The thrust can be forced to any direction (range from 0° to 360°) by changing the motion of the blades without setting a rudder separately. And the movement of the blades and the control mechanism is completely innovative. What's more, this propeller has a simple structure, light weight, low manufacturing cost and good operation characters, which leads the propeller to be less affected by the ship working condition. Also the maneuverability remains good when the ship speed is low even the speed is 0.

To better understand the characteristics of propeller, the

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work in this paper was focused on how to change the direction of thrust accurately, the realization of alternating speed of the propeller under a constant diesel engine speed and the hybrid power system. The latest research would be presented on a new hybrid power system by using the Vertical-axis Propeller based on its advantages.

II. DESIGN OF VERTICAL-AXIS PROPELLER

The propeller has a symmetrical structure shown in Fig.1. It has the following characteristics:

- Blades do rotation around its own axis with a constant speed and revolution around the disk at the same time.
- Blades' rotation speed is half of the revolution speed.
- Symmetrical blades.
- Due to the simple structure and light weight it can operate at high speed.
- Revolution speed can be just continuously without any change of diesel engine through its own auxiliary transmission mechanism.

The propeller is composed of gear bank, gear rings, auxiliary transmission mechanism, axis and blades. The steering engine can change phase angle of blades through the steering gear.

The key structure is auxiliary transmission mechanism. Fig.2 shows the simplified relationship between the main system and auxiliary system.

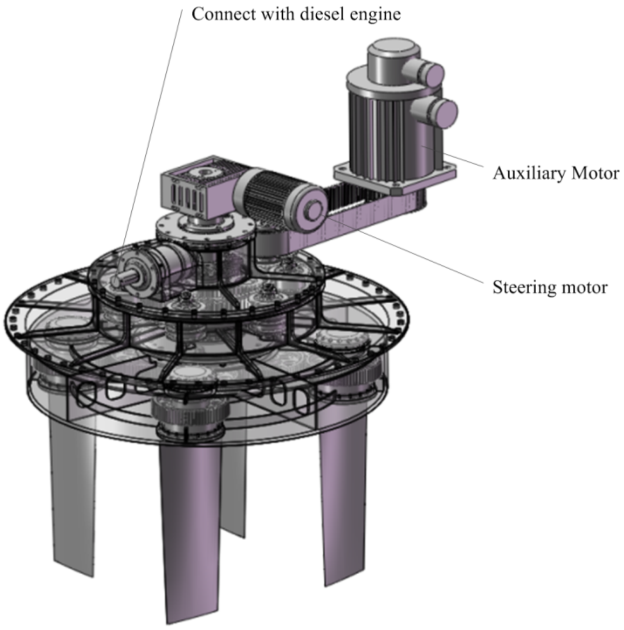

Fig. 1.Schematic of the Vertical-axis Propeller

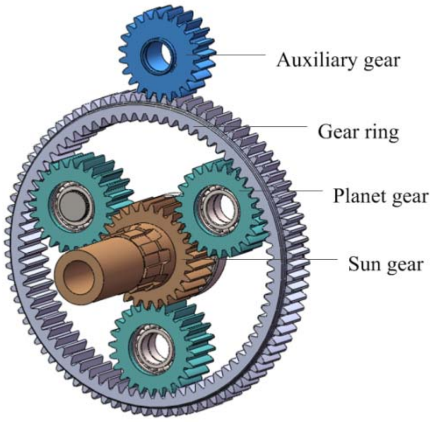

Fig. 2.Auxiliary transmission mechanism of the power system.

The auxiliary transmission mechanism will experience two states at its working time, e.g. absorbing excess power from diesel engine and providing auxiliary power. The power of diesel engine inputs from sun gear. The blades are driven by planet gears. The propulsion system has a set of auxiliary power system which inputs power from auxiliary gear. On one hand, the auxiliary system controls the motion of the gear ring to change the motion of planet gear. As a result, it changes the rotation of blades. On the other hand, the redundant power of diesel engine can be outputted through auxiliary gear and then Stored in the battery. So the propeller is easy to realize speed change, energy storage and emergency power supply by controlling the auxiliary power system instead of changing the diesel engine

III. PERFORMANCE OF VERTICAL-AXIS PROPELLER

In order to generate thrust, each blade of the propeller performs a rotation around its own axis and then they are superimposed into a uniform motion. The value of thrust is determined by diesel engine and blade position, while its direction is determined by the phase angle range from 0° to 360°. The magnitude and the direction of thrust of the VSP are both controlled by a control rod[4]. The blade excursion of VSP determines the amount of thrust. Be different with the VSP, vertical-axis propeller are controlled by gears.

The propeller can guarantee fast and precise adjustment of direction both in emergency or normal state. The principle of steering direction is shown in Fig.3.[8] V_e is the ship speed after considering the flow velocity, u is the tangential velocity of disk. W is sum velocity flowing through the cross-section of blade，N is control point，$\overline{NN'}$ is the control vector，α is the angle of attack. R, A, W are the resultant force, lifting force and drag force in the cross-section of blade, respectively.

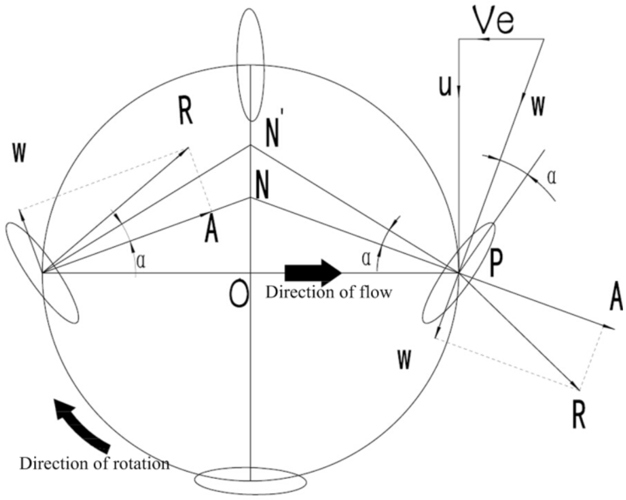

Fig. 3. Principle of direction adjustment

When point N coincides with the disk center O, the chord line of blade coincides with the tangent line of that point so that the direction of blade is consistent with the tangent line. it can obtain that

$$V_e = 0 \tag{1}$$

At this moment, the velocity of blade is zero and there has no thrust generated by water to push the blades. As a result, the ship cannot move forward.

When the point N deviates from point O, the setover ON exists. From Fig.3, W is perpendicular to NP. U is perpendicular to OP. Then,

$$\frac{ON}{V_e} = \frac{OP}{U} = \frac{NP}{W} \tag{2}$$

The eccentricity of point N is,

$$\mathrm{e} = \frac{ON}{R} \tag{3}$$

Where R is circle radius. Therefore,

$$\mathrm{U} = \omega \cdot \mathrm{R} \tag{4-1}$$

$$V_e = e \cdot R \cdot \omega \tag{4-2}$$

$$\mathrm{W} = \mathrm{NP} \cdot \omega \tag{4-3}$$

Where ω is the rotational frequency of disk. After one revolution of propeller, the advanced distance of point O can be regard as the pitch, which is equal to,

$$\mathrm{H} = 2\pi \cdot \mathrm{e} \cdot \mathrm{R} \tag{5}$$

So according to the above equations, the ship speed is related to the eccentricity and disk rotational speed. When the point N moves to point $N^{'}$, it means the motion of blade has changed, so the direction and magnitude of thrust will also change. In addition, the existence of attack angle will result in the generation of lifting force at the rotating blades surface, which plays a role of propulsion in forward direction. However, the lifting force keeps changing during one rotational period of blade. [9] As a consequence, the component force perpendicular to the direction of motion should be offset with each other to keep the thrust acting in the same direction when the blades are at different position.

In order to verify the propeller's steering performance, a manual steering system was designed based on motor. The system was installed in the test boat. The equipment for the experiment mainly included a Vertical-axis Propeller, angular transducer, handle, control box and a motor of which the rated power was 1.5kw and the rated speed was 1400r/min.

There were belt pulley, linkage mechanism and reducer between the motor and propeller. The reduction ratios of those connecting organizations were 2 to 1, 4 to 1 and 100 to 1 separately. Through the operating handle, the propeller turned left or turned right to reach the setting angle and then recorded the time. Some results are shown in table.1.

Table1

Angle(°)	Current(A)	Voltage(V)	Time(s)
0-30	5.4	220	3.2
30-60	5.4	220	3.2
60-90	5.4	220	3.5
90-120	5.4	220	3.4
120-150	5.4	220	3.1
150-180	5.4	220	3.2

We could see from the experiment that the blades could be operated in any direction and the response time was steady.

IV. APPLICATION OF VERTICAL-AXIS PREPELLER

The special auxiliary power system of propeller can realize speed change, energy storage and emergency power supply without changing the working state of diesel engine. As shown in Fig.4, the operation of the whole system is conformed to the energy management strategy. The operating mode of the motor depends on the energy requirement.

This hybrid power system has three working modes. One is pure electric propulsion mainly for the place having high requirement of noise and emission. The second is pure diesel mode mainly for the situation of power shortage. The third is hybrid propulsion mode primarily used for larger load or battery charging. The adjustment of operating modes is depended on the flow speed, load demand and power capacity in order to save energy and avoid the frequent change of working state of the diesel engine.

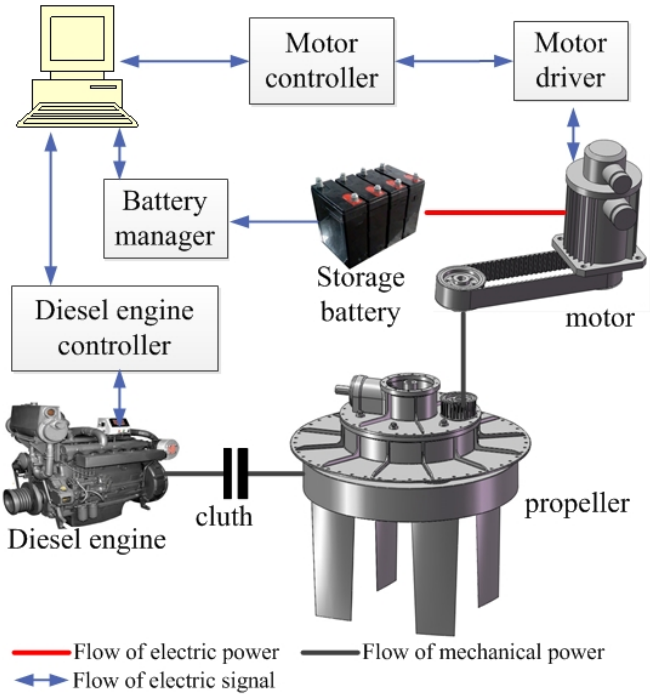

Fig. 4. The frame of the hybrid power system

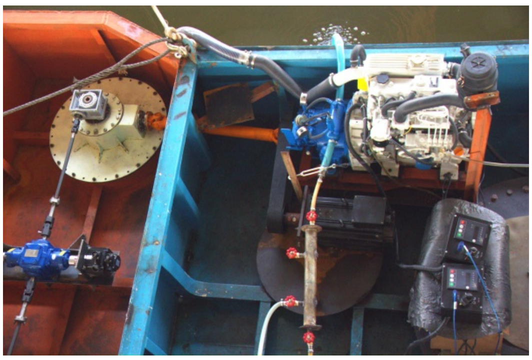

Fig. 5. The experimental platform

V. CONCLUSION

- A new Vertical-axis Propeller was designed, which has simple structure, light weight and strong maneuverability.
- The steering ability of the propeller has been tested through the experiment, which shown that the propeller could achieve the range of steering direction from 0° to 360° smoothly.
- Based on its own auxiliary transmission mechanism, the propeller has a good application in the hybrid system with three working patterns.

ACKNOWLEDGEMENT

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